Eur J Appl Physiol (2012) 112:1577–1585
DOI 10.1007/s00421-011-2124-8

ORIGINAL ARTICLE

Ankle proprioception is not targeted by exercises on an unstable surface

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Received: 9 April 2011 / Accepted: 10 August 2011 / Published online: 21 August 2011

Abstract Laboratory study using a repeated measures design. The aim of this study was to determine if ankle proprioception is targeted in exercises on unstable surfaces. Lateral ankle sprain (LAS) has recurrence rates over 70%, which are believed to be due to a reduced accuracy of proprioceptive signals from the ankle. Proprioceptive exercises in rehabilitation of LAS mostly consist of balancing activities on an unstable surface. The methods include 100 healthy adults stood barefoot on a solid surface and a foam pad over a force plate, with occluded vision. Mechanical vibration was used to stimulate proprioceptive output of muscle spindles of triceps surae and lumbar paraspinal musculature. Each trial lasted for 60 s; vibration was applied from the 15th till the 30th second. Changes in mean velocity and mean position of the center of pressure (CoP) as a result of muscle vibration were calculated. Results show that on foam, the effect of triceps surae vibration on mean CoP velocity was significantly smaller than on a solid surface, while for paraspinal musculature vibration the effect was bigger on foam than on solid surface. Similar effects were seen for mean CoP displacement as outcome. Exercises on unstable surfaces appear not to target peripheral ankle proprioception. Exercises on an unstable surface may challenge the capacity of the central nervous system to shift the weighting of sources of proprioceptive signals on balance.

Keywords Postural control · Proprioception · Functional ankle instability · Rehabilitation

Communicated by Fausto Baldissera.

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Introduction

The ankle is injured in one-third of all sport injuries, with lateral ankle sprain (LAS) being the most common type of ankle injury. Recurrence rates for LASs are high and have been reported to be over 70% (Yeung et al. 1994). The reason for the high recurrence rate is believed to be a reduced accuracy of proprioceptive signals from the ankle which leads to a functional instability (Hertel 2000).

There is evidence to support the presence of proprioceptive impairments in acute and recurrent ankle sprain. In a recent systematic review, Munn et al. (2010) found evidence for a reduced capacity to detect passive movements in people with functional ankle instability.

In line with this, rehabilitation programs for patients with functional ankle instability often comprise so-called "proprioceptive" exercises, which mostly consist of balancing activities in which persons stand on some form of unstable surface such as a wobble board, foam or ankle disc. It is assumed that standing on unstable surfaces stimulates the use of proprioceptive signals from around the ankle and in this way is beneficial for ankle stability.

These rehabilitation programs are effective in reducing the amount of ankle sprain recurrences. In a meta-analysis Van der Wees et al. (2006) found a pooled relative risk of 0.38, which can be considered as a substantial clinical effect. After their review was written, two randomized controlled trials were published. Both confirmed the conclusion that proprioceptive exercises are effective in preventing recurrences of ankle sprains (Hupperets et al. 2009b; Mohammadi 2007).

However, it is questionable whether rehabilitation programs indeed target ankle proprioception deficits as the mediating pathway to a reduction in ankle injuries. When standing on an unstable surface, ankle angles are not informative with respect to the overall body orientation relative to the surface. Furthermore, ankle responses may be less effective in control of balance than more proximal responses (e.g. a hip strategy) (Otten 1999). Although some studies showed beneficial effects of exercise programs on proprioceptive outcomes, like muscle reaction times (Hughes and Rochester 2008) and postural sway (Hughes and Rochester 2008), others found no evidence for an effect of rehabilitation programs on postural sway (van der Wees et al. 2006). Moreover, both postural sway and muscle reaction time are characteristics that in addition to peripheral proprioceptive signals are dependent on an abundance of other variables.

Joint position sense is more directly related to proprioceptive signals, but the effect of training on joint position sense and proprioceptive exercises has also been questioned (Ashton-Miller et al. 2001). Mechanisms behind training could be a change in the number of peripheral receptors, for which the evidence is lacking, or increased fusimotor firing rate, which might increase the gain of muscle spindles, but has never been shown to increase proprioceptive acuity in humans.

Ashton-Miller et al. (2001) conclude that central mechanisms could explain how training might modify proprioception. While several studies have reported positive effects of training on position sense (Kynsburg et al. 2006; Lee and Lin 2008), Bernier and Perrin (1998) found improvements in position sense after an exercise program, but these improvements did not differ significantly from the control groups. Recently, in a critical evaluation of the available literature, Hupperets et al. (2009a) concluded that the aforementioned effects on postural sway and joint position sense are not necessarily a consequence of the exercises, but may be due to a learning effect created by the repeated measurements. They state that the pathway through which sensorimotor training reduces re-injury risk remains unclear.

Another finding that contradicts the central role of ankle proprioception in exercises on unstable surfaces is that on such unstable surfaces, stimulating muscle spindle output of Triceps Surae has a smaller effect on Centre of Pressure (CoP) position than on a solid surface (Brumagne et al. 2008; Ivanenko et al. 1999).

Muscle spindles play a major role in proprioception (Cordo et al. 1995; Goodwin et al. 1972a; Roll and Vedel 1982). In studies on the role of proprioception in standing, vibration is used to analyze the relative contribution of a peripheral proprioceptive signal to the total motor output. Vibration is a potent stimulus for primary and secondary muscle spindles endings and Golgi tendon organs in muscles (Burke et al. 1976a, b; Roll et al. 1989). Vibration induces a bias into the muscle spindle output. The vibrated muscle is usually perceived to be longer than it actually is (Cordo et al. 2005; Goodwin et al. 1972b; Roll and Vedel 1982). This lengthening illusion under vibration will cause corrective displacement of the center of mass, related to the amount in which the central nervous system uses these signals for postural control. For example, when triceps surae muscles are vibrated in standing, a backward shift in CoP takes place if the central nervous system is using these signals for postural control (Brumagne et al. 2004; Crowe and Matthews 1964). This displacement decreases when persons are placed on foam (Brumagne et al. 2008) or on a wobble board (Ivanenko et al. 1999). In Brumagne's experiment, the opposite effect was seen for vibration of paraspinal musculature: the magnitude of CoP displacement was bigger on foam than on solid surface, which suggest that a shift in weighting of proprioceptive signals from ankles to the lower trunk took place (Brumagne et al. 2008).

Though these results are indications that ankle proprioception is used less on unstable surfaces, it is not definite proof. CoP displacement under vibration is the mean of changes in position of the CoP and therefore it does not reflect the dynamic use of spindle signals in the continuous control of balance, as this entails quick responses.

We hypothesized that ankle proprioception is not targeted by exercises on an unstable surface. Proprioceptive signals from other body sites, vestibular information or the capacity of the central nervous system to switch between these systems according to external conditions seem more appropriate candidates to fulfill this task. We therefore analyzed the effect of vibration on balance, as measured by CoP velocity, in addition to the effect on a shift in CoP position. Mean CoP velocity is the most commonly used variable to study balance control. If vibration on an unstable surface not only introduces a smaller bias in CoP position, but also has a lesser effect on sway velocity than on a stable surface, then we could conclude that standing on an unstable surface is not facilitating the use of proprioceptive signals from the ankles in balance control. In order to determine the effect of foam on the use of proprioceptive signals from the lumbar spine in postural stability, we also vibrated paraspinal musculature of the lumbar spine. If our hypothesis is correct, the pathway from rehabilitation to reduced ankle sprains has to be reconsidered, which could lead to more effective exercises in ankle sprain rehabilitation.

Methods

Subjects

One hundred healthy subjects, 81 males, 19 females (age 41.6 years ± 10.8, weight 81.66 kg ± 11.8, height 179.9 cm ± 8.9) were randomly drawn from the participants of the Utrecht Police Lifestyle Intervention Fitness and Training study, a voluntary fitness and lifestyle test for working police employees in Utrecht, The Netherlands. Measurements took place between December 2007 and June 2008. All subjects provided their written informed consent and the protocol was approved by the Ethical Committee of Utrecht University Medical Centre. None of the participants presented any known neurological disorders, vestibular impairment or pathologies of the lower extremities.

Experimental procedure

Participants stood barefoot on a force plate (Kistler 9286 AA) in a comfortable position (feet shoulder width, arms hanging loosely by the side). Subjects were asked to stand relaxed and immobile, and to face straight ahead with eyes open. Foot position was marked on a transparent sheet to ensure an equal position across trials. Nine test conditions were used (Table 1). In all trials, with exception of the first one, vision was occluded by means of taped safety glasses. The first three trials were performed for another purpose and are not included in the analysis; (1) upright standing with transparent safety glasses and with eyes open, (2) upright standing, and (3) upright standing on an foam support surface (Airex balancepad, 6 cm thick). In trial 4, a muscle vibrator (Maxon motors Switzerland) was attached with Velcro straps over the lower lumbar paraspinal musculature, in trial 5 the muscle vibrator was attached bilaterally to the triceps surae muscles, also with Velcro straps. Muscle vibration, with a frequency of 70 Hz and amplitude of approximately 0.5 mm, was initiated 15 s after the start of the trial for the duration of 15 s. Each trial lasted for 60 s, with subjects standing on the force plate for 5 s before the trial started. These characteristics were proven to induce a significant effect on CoP position, with a limited number of subjects losing their balance during vibration (Brumagne et al. 2004). The same procedure was repeated in trials 7, 8 and 9 with subjects standing on the foam surface. A research assistant was always standing directly behind the participant to prevent actual falls. Trials in which the research assistant touched the participant to prevent him or her from falling were discarded and repeated after a break of at least five minutes. In trials 8 and 9, limits of stability were tested on respectively foam and rigid surface, to control for possible ceiling effects due to a smaller area available for a stable position on foam. In these trials, subjects were asked to lean as far as possible forward and backward both during five seconds without bending hips or knees.

Table 1 Sequence of experimental trials

Trial	Vision	Surface	Vibration
1	Transparent glasses	Solid	No
2	Occluded vision	Solid	No
3		Foam	No
4		Solid	Paraspinal musculature
5		Solid	Triceps surae
6		Foam	Paraspinal musculature
7		Foam	Triceps surae
8		Foam	Limits of stability, no vibration
9		Solid	Limits of stability, no vibration

Data reduction and statistical analysis

For trials 4–7 (vibration of paraspinal muscles and triceps surae), mean CoP position in anterior/posterior direction and mean total CoP velocity (V) were computed, both for the previbration and the during vibration period. These variables were used to calculate the effect of vibration using the following equation for mean total CoP velocity: V 15th–30th second (during muscle vibration)/V 0th–15th second (preceding muscle vibration). This formula results in a unitless variable: the proportion increase in velocity due to vibration. The shift of the CoP position was calculated by subtracting the mean CoP position in anterior-posterior direction before vibration 0th–15th second), from the mean CoP position in anterior posterior direction during vibration (15th–30th second). This results in a variable that describes the displacement under vibration in centimeters.

To identify the limits of stability, the moving average positions across trials 8 (on a foam surface) and 9 (on a solid surface) were calculated with windows of 1 s. Maximal and minimal values of the moving average were used as respectively anterior and posterior limit of stability. Subsequently, we calculated the distance of the CoP position during vibration in trial 4–7, to the limit of stability in trial 9 and 10. Vibration of the paraspinal muscles led to a forward CoP displacement, and vibration of the triceps surae to a backward displacement. We therefore subtracted the mean position under vibration of the lumbar spine from the anterior limit of stability (anterior limit trial 9: mean position under vibration trial 4; anterior limit trial 8: mean position under vibration trial 6), and mean position under vibration of triceps surae from the posterior limit of stability (posterior limit trial 9: mean CoP position under vibration trial 5; posterior limit trial 8: mean CoP position trial 8).

Force plate data were sampled at 200 Hz using Bioware 3.24 software. Matlab 7.0.1 was used to low-pass filter raw data with a Butterworth filter with a cutoff frequency of 3 Hz, and to compute outcome variables. Synchronization of the force plate measurements with activation of the vibrators was controlled by custom-made software.

Paired sample t tests were used to test whether there were significant differences between the mean position and velocity of the CoP between pre-vibration period and vibration period, to assure the significance of the postural effects due to the muscular vibration. As primary outcome, we used both mean CoP displacement under vibration and change in CoP velocity under vibration as dependent variables in two separate analyses. To test for significance of differences, we first performed a 2×2 factorial ANOVA on two factors (surface and muscle) and their interaction. To explore the effect of surface on vibration within each muscle group, the 2×2 ANOVA was broken down in two paired sample t tests. Alpha was set at 0.05 for all tests. Statistics were performed with SPSS 18.0.

Results

All differences between the mean position and velocity of the CoP between pre-vibration period and vibration period were significant at $p \leq 0.002$. Seventeen subjects had to be tested a second time because the research assistant had to help them keep their balance. All events in which help was needed took place during trial 6, with triceps surae vibration on a solid surface. No subjects lost their balance more than once. Figure 1 shows a representative trial with triceps vibration on solid surface, illustrating that backward CoP displacement and increased CoP velocity coincide with vibration. Means and standard errors of CoP displacement and increase in CoP velocity are graphically presented in Fig. 2. Means and standard deviations of CoP position and velocity, before and during vibration, are presented in Table 2.

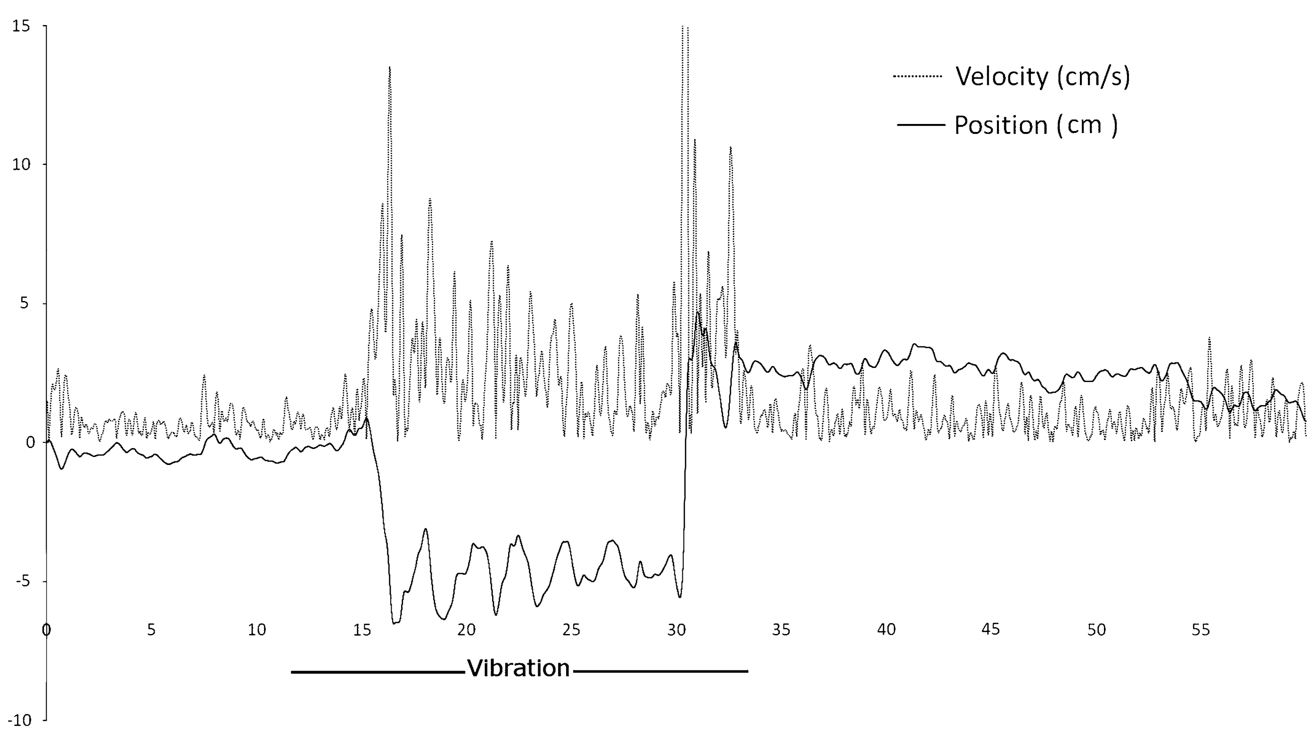

Fig. 1 Representative example of fore-aft position and velocity of the centre of pressure during trial 5: firm surface, vibration on triceps surae

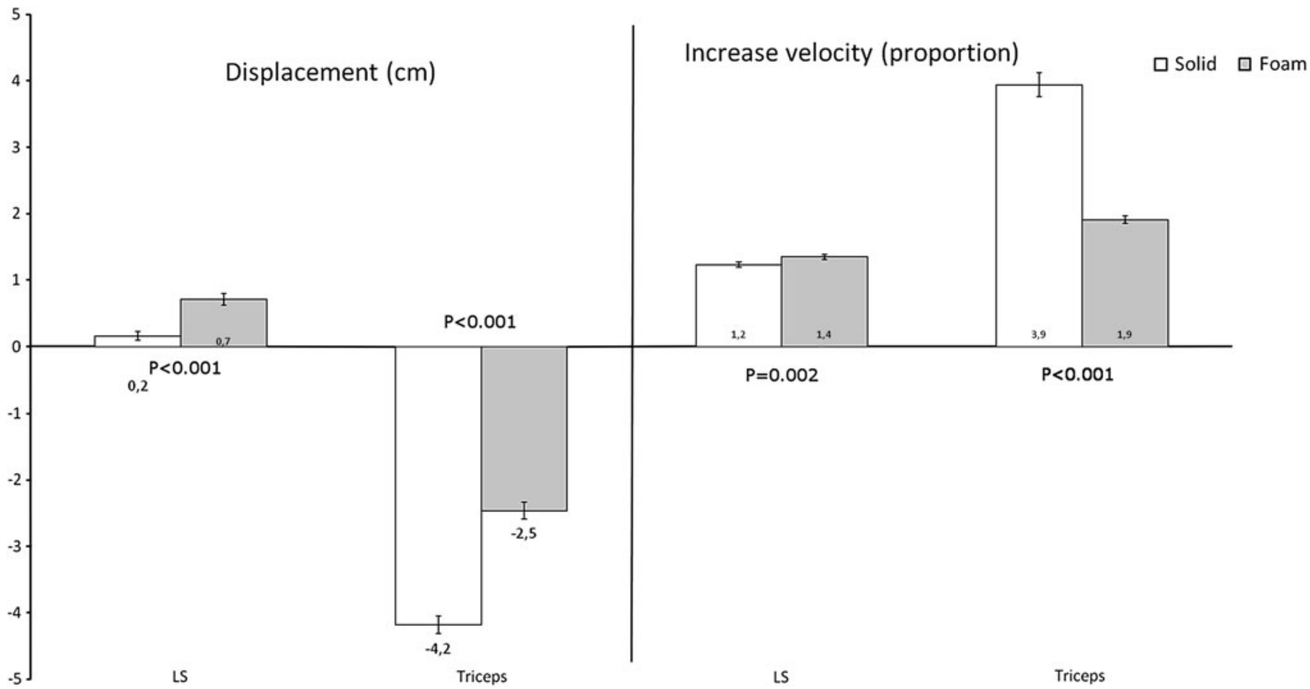

Fig. 2 Mean and standard error of CoP displacement in centimeters and increase in CoP velocity in proportion (unitless) under influence of vibration. *LS* lumbar spine paraspinal musculature, *Tib* tibialis, *Triceps* triceps surae

Table 2 CoP position and velocity before (pre) and during vibration

CoP position (cm)	Previbration	During vibration	Displacement
Trial 4 LS solid	−0,169 ± 0,505	−0,007 ± 0,408*	0,162 ± 0,686
Trial 6 LS foam	−0,036 ± 0,565	0,674 ± 0,659**	0,709 ± 0,917**
Trial 5 Triceps solid	0,334 ± 0,605	−3,841 ± 1,14**	−4,175 ± 1,293
Trial 7 Triceps foam	0,156 ± 0,657	−2,307 ± 0,898**	−2,462 ± 1,293**
CoP velocity (cm/s)	**Previbration**	**During vibration**	**Increase velocity**
Trial 4 LS solid	1,495 ± 0,66	1,75 ± 0,76**	1,233 ± 0,396
Trial 6 LS foam	4,221 ± 1,436	5,41 ± 1,732**	1,349 ± 0,411*
Trial 5 Triceps solid	1,294 ± 0,506	4,66 ± 1,684**	3,941 ± 1,796
Trial 7 Triceps foam	3,563 ± 1,036	6,553 ± 1,897**	1,917 ± 0,552**

Means and standard deviations. $^{*}p \leq 0.02$, $^{**}p < 0.001$. *P* values refer to *t* test pre an during vibration (3rd column), and t test between effect of vibration on solid surface and on foam (4th column)

Center of pressure displacement

Center of pressure displacement during vibration differed between muscle groups and was the largest for vibration of the triceps surae ($F(1,99) = 892.146$, $p < 0.001$). Mean CoP displacement during vibration of paraspinal musculature was in the forward direction as opposed to vibration of triceps surae musculature. Surface had a significant influence on the magnitude of the CoP displacement ($F(1,99) = 203.575$, $p < 0.001$), but the effect of surface differed as to which muscle was vibrated ($F(1,99) = 64.482$, $p < 0.001$).

The effect of vibration on triceps surae was smaller on foam than on a solid surface (-2.46 ± 1.29 cm vs. -4.18 ± 1.29 cm, $p < 0.001$). For vibration of paraspinal musculature, the magnitude of CoP displacement was bigger on foam than on solid surface (0.71 ± 0.92 cm vs. 0.16 ± 0.69 cm, $p < 0.001$).

Center of pressure velocity

The increase in CoP velocity as a consequence of vibration differed between muscle groups ($F(1,99) = 290.751$, $p < 0.001$), with the largest effect for vibration of the triceps surae. Surface had a significant influence on the effect of vibration on mean CoP velocity ($F(1,99) = 117.337$, $p < 0.001$) but the effect of surface differed as to which muscle was vibrated ($F(1,99) = 168.521$, $p < 0.001$).

The effect of vibration on triceps surae was smaller on foam than on a solid surface: CoP velocity increased during vibration with a factor 1.91 ± 0.55 versus 3.94 ± 1.8 on solid surface ($p < 0.001$). For vibration of paraspinal musculature, the increase in CoP velocity was bigger on foam than on solid surface (1.35 ± 0.41 vs. 1.23 ± 0.4, $p = 0.019$).

Limits of stability

The possibility of a ceiling effect was investigated by subtracting mean positions during vibration from the limit of stability. Distance to the limit of stability was smallest during vibration of the triceps on a solid surface (2.5 ± 1.7 cm), and increased during standing on foam (2.76 ± 1.37 cm). During vibration of the lumbar spine these values were, respectively, 7.1 ± 1.66 cm and 5 ± 1.32 cm.

Discussion

We showed in a population of 100 healthy middle aged subjects, that proprioceptive signals from the triceps surae are used less in maintaining upright stance on foam than on a solid surface. For paraspinal muscles, we found the opposite: proprioceptive signals were used more when standing on foam. We used both mean CoP displacement and mean CoP velocity as outcome variables. Mean displacement under vibration can be seen as a measure of a new set point for proprioceptive information. The findings in CoP displacement under vibration are in line with the findings of Brumagne et al. (2008), and Ivanenko et al. (1999), who found the same decrease in gain of ankle proprioception signals on an unstable surface. Brumagne et al. (2008) also showed more CoP displacement when vibrating paraspinal muscles while standing on foam than on a solid surface. With respect to mean CoP velocity, to our knowledge, this is the first study in which this parameter was used to demonstrate a shift in proprioceptive weighting. The increase in mean CoP velocity due to stimulation of sensory input under muscle vibration can be interpreted as an increase of noise in the postural control system and as an indication of reduced dynamic stability. In contrast, the shift in average CoP with vibration is commonly interpreted as a change in the set point of the balance control system. Consequently, a smaller increase under vibration on foam than on a rigid surface strongly supports lower weighting of proprioceptive ankle signals in maintaining dynamic stability on foam. This finding may have significant implications for clinical practice as unstable surfaces do not seem to target proprioceptive training of ankle musculature.

Freeman et al. (1965) were the first to design a functional ankle rehabilitation program based on the premises that proprioception deficits have a causal effect on re-injury. They state that mechanoreceptors in the lateral ankle ligaments (among other receptors) control the precise contractions of the calf muscles which must occur if the foot is to remain stable on uneven ground. A traction injury will lead to the rupture of nerve fibers as well as of collagen fibers (Freeman et al. 1965). If the ligaments heal in an elongated state, the mechanoreceptors will misinterpret the inversion angle (Konradsen 2002).

In our experiment, we stimulated muscle spindle output, not afferent output from ligamentous mechanoreceptors. We think this choice is justifiable for two reasons. First, results in microneurography studies have demonstrated a major role of muscle spindles in proprioception (Cordo et al. 1995; Goodwin et al. 1972a; Roll and Vedel 1982) and muscle spindles are the primary sensory resource of information for maintaining balance during upright stance (Fitzpatrick et al. 1994; Fitzpatrick and McCloskey 1994). Second, anesthetizing joint receptors only results in an increased positioning error in passive repositioning (Konradsen et al. 1993). It does not affect active positioning errors (Konradsen et al. 1993), nor does it cause a change in motor neuron excitability (Sabbahi et al. 1990). Intra-articular anesthetic blocks in healthy persons do not result in a change in movement sense (Down et al. 2007), nor to a change in peroneal reaction time (Khin et al. 1999). In subjects with functional ankle instability, it even results in an improvement in peroneal reaction time, which the authors explained by the suppression of gamma motor activity induced by inflammation of the sinus tarsi (Khin et al. 1999).

It could be argued that our findings are biased because standing on foam leads to a smaller limit of stability and as a consequence of this there is a "ceiling effect". Subjects do not have as much "reserve space" and therefore range and standard deviation cannot be increased as much as on a rigid surface without the subject falling. Also, the increased threat of falling will cause more attention to proprioceptive and vestibular information. Therefore a slighter disturbance of balance will receive a more adequate and quicker motor response, resulting in a smaller increase in CoP velocity. If this was true, it could be expected that balance is most endangered when vibrating muscles on foam surface. In fact, no subject lost balance on foam surface whereas 17 from 100 subjects needed help from the research assistant to prevent them from falling when standing on a firm surface. Moreover, the distance between the limit of stability and maximum posterior position during vibration of the triceps surae, which was the muscle reacting the strongest on vibration, was even larger on foam than on solid surface. Also, the effect of paraspinal muscle vibration was actually increased despite the decrease of distance to anterior limit of stability.

Applying foam also leads to a larger surface height (Az) and in this way seems a potential threat to the accuracy of the calculated CoP position. However, the influence of surface height is dependent on the magnitude of the shear forces in anterior-posterior and medio-lateral direction. These forces are only present when subjects accelerate or decelerate and have to be multiplied with surface height (0.06 m) to calculate the effect on CoP position. Compared to the other factors in this calculation (the moments around x and y axis), this effect is very small and leads to non-significant changes of less than 0.1% in CoP position.

We used a fixed order of trials in our experiment. This could lead to a bias in outcome due to adaptation of muscles to vibration (Caudron et al. 2010). However, where this effect was found over a time interval of 10–20 s, we took at least 5 min between two trials on the same muscle. For another experiment (unpublished data), we used exactly the same setup for triceps surae vibration, but with four consecutive trials within 5 min. Subjects showed in trial four 83% of the CoP displacement, and 59% of the increase in CoP velocity of trial one, while these numbers are, respectively, 57 and 48% for the comparison of vibration effects between solid surface and foam in this study. Therefore, the differences between vibration on solid surface and on foam cannot fully be explained by an adaptation effect, not even when adaptation in the two trials in this study was equal to adaptation in the four successive trials of our unpublished data. Also, when adaptation would have biased our experiment, the main finding in our study would even be stronger as the effect of vibration on paraspinal musculature in the second trial might even be higher.

We postulate two explanations for our findings. For both explanations, we apply the basic principle that the integration of sensory signals is dynamically regulated to adapt to changing environmental conditions and the available sensory information (Mahboobin et al. 2009). The first possible explanation is that proprioceptive signals from the ankle become unreliable on an unstable surface and therefore the central nervous system places more weight on other sources of information about spatial orientation of the body. Muscle spindle output is determined by muscle length and changes in muscle length. In standing on a solid surface a pendular movement of the body leads to a change in ankle joint angle and, as a consequence of this, to a change in muscle length of the muscles surrounding the ankle. When standing on foam or wobble board, a change in ankle joint angle and muscle length may occur without any change in body orientation and vice versa. Therefore, signals from muscle spindles do no longer reflect the orientation of the body relative to the gravitational field and it can be expected that the central nervous system reduces weighing of sources of proprioceptive signals that are inconsistent with other sources of sensory information.

A second explanation is on a shift in motor strategy used to maintain balance. It is widely accepted that in standing the body is controlled in the sagittal plane more or less as an inverted pendulum rotating around the ankle joints. In this strategy, moments exerted around the ankle joint lead to a change in orientation of the body above the ankle and are used to prevent falling. On foam the effect of moments around the ankle on balance is reduced as ankle moments lead to deformation of the foam surface. This is somewhat comparable to standing on a narrow ridge. Otten (1999) showed that in this condition subjects switch to a hip strategy in which moments around the hip are used to change the position of the center of mass. These moments are induced by shear forces at the surface and not by ground reaction forces. By moving around the hip, sensory signals from the lower back and hip are increased and may be weighted higher in determining the postural response. It may be that subjects standing on foam also make more use of a hip strategy.

These explanations are not mutually exclusive and both are in line with the findings of Ivanenko et al. (2000), who measured CoP displacement under vibration of shank muscles on a seesaw that could be stabilized in separate directions. Postural reactions to vibration were present on those supports that were stable in the sagittal direction, but not on supports that were unstable in sagittal directions and stable in all other directions.

We believe that both explanations can account for the decreased effect of triceps surae vibration on foam and the increased effect of paraspinal muscles vibration on foam. Standing on an unstable surface induces a shift in proprioceptive weighting away from the ankle, which is obviously the opposite of what is aimed for in proprioceptive exercises for the ankle. This implies that not peripheral ankle proprioception plays an intermediating role in the results of functional ankle rehabilitation, but other body region's proprioceptive information, the vestibular system or central proprioceptive weighing mechanisms.

Although research in this field is sparse, there are other studies that confirm the dependency of the lower limb injury risk on proprioception of other body areas. For example, Zazulak et al. (2007) showed that the accuracy of active proprioceptive trunk repositioning predicted future knee injuries with 90% sensitivity and 56% specificity in female athletes. Also, motor control variables in more proximal areas were shown to be related to ankle injury. Van Deun et al. (2007) showed that subjects with chronic ankle instability showed significantly later onset times for the ankle, hip, and hamstring muscles compared with control subjects when switching form bipedal to unipedal stance.

It has not escaped our notice that the results of our experiment only point out that exercises, as commonly used to train ankle proprioception, are effective for other reasons than enhancing ankle proprioception. Our findings do not rule out a causal relation between ankle proprioception and re-injury. Although position and movement sense are impaired in ankle injuries, there are to our knowledge no well developed longitudinal studies in which a causal relationship between proprioceptive deficits and ankle re-injury is investigated. If proprioceptive impairments cause ankle (re-)injuries, exercises that target peripheral ankle proprioception are indicated in addition to the current exercises on unstable surfaces. Manipulating other peripheral proprioceptive signals, for example by vibrating other musculature, or manipulating vestibular information by tilting the head backwards, could be options. Also, it has been shown that reliance on ankle proprioception increases when trunk muscles are fatigued (Vuillerme and Pinsault 2007).

Conclusion

Results from the present study showed that exercises at unstable surfaces do not challenge peripheral ankle proprioception in maintaining balance. It is more plausible that exercises on an unstable surface challenge other proprioceptive systems or body regions, or the capacity of the central nervous system to shift the weight of the individual sources of information. Further research should focus on the predictive value of ankle proprioception deficits and on exercises that target peripheral ankle proprioception. Clinicians could then integrate these conditions in rehabilitation programs.

Conflict of interest The authors declare that they have no conflict of interest.

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